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Keywords
Nondestructive Evaluation

Disciplines
Materials Science and Engineering

ENGINE COMPONENT RETIREMENT-FOR-CAUSE:
A NONDESTRUCTIVE EVALUATION (NDE) AND FRACTURE MECHANICS
BASED MAINTENANCE CONCEPT

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ABSTRACT

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INTRODUCTION

Historically, methods used for predicting the life of gas turbine engine rotor components have resulted in conservative estimation of useful life. Most rotor components are limited by low cycle fatigue, generally expressed in terms of mission equivalency cycles. When some predetermined cyclic life limit is reached, components are retired from service.

Total fatigue life of a component consists of a crack initiation phase and a crack propagation phase. Engine rotor component initiation life limits are analytically determined using lower bound LCF characteristics. This is established by a statistical analysis of data indicating the cyclic life at which 1 in 1000 components, such as disks, will have a fatigue induced crack of approximately 0.03 inch length. By definition then, 99.9% of the disks are being retired prematurely. It has been documented that many of the 999 remaining retired disks have considerable useful residual life. Retirement for Cause (RFC) would allow each component to be used to the full extent of its safe total fatigue life, retirement occurring when a quantifiable defect necessitates removal of the component from service. The defect size at which the component is no longer considered safe is determined through nondestructive evaluation (NDE) and fracture mechanics analyses of the disk material and the disk fracture critical locations, the service cycle and the overhaul/inspection period. Realization and implementation of a Retirement for Cause Maintenance Methodology will result in system cost savings of two types: direct cost savings resulting from utilization of parts which would be retired and consequently require replacement by new parts; and indirect cost savings resulting from reduction in use of strategic materials, reduction in energy requirements to process new parts, and mitigation of future inflationary pressure on cost of new parts.

RETIREMENT FOR CAUSE METHODOLOGY

Philosophy - The fatigue process for a typical rotor component such as a disk can be visualized as illustrated in Fig. 1. Total fatigue life consists of a crack initiation phase followed by growth and linkup of microcracks. The resulting macrocrack(s) would then propagate subcritically until the combination of service load (stress) and

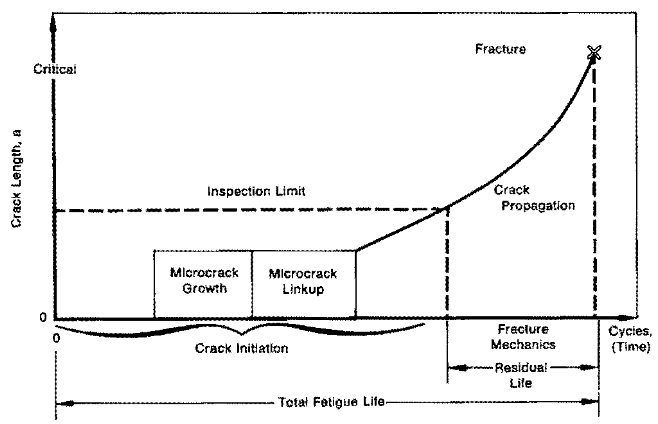

Fig. 1 Total fatigue life segmented into stages of crack development, subcritical growth, and final fracture.

crack size exceeded the material fracture toughness. Catastrophic failure would result had not the component been retired from service. To preclude such cataclysmic disk (and possibly engine) failures, disks are typically retired at the time where 1 in 1000 could be expected to have actually initiated a short (0.03 in.) fatigue crack. By definition 99.9% of the retired disks still have useful life remaining at the time they are removed from service. Under the Retirement-for-Cause philosophy, each of these disks could be inspected and returned to service. The return-to-service (RTS) interval is determined by a fracture mechanics calculation of remaining propagation life from a crack just small enough to have been missed during inspection. This procedure could be repeated until the disk has incurred measurable damage, at which time it is retired for that reason (cause). Retirement for Cause is a methodology under which an engine component would be retired from service when it had incurred quantifiable damage, rather than because an analytically determined minimum design life had been reached. Its purpose is not to extend the life of a rotor component, but to utilize safely the full life capacity inherent in that component.

Residual Life - For simplicity this paper will consider component life limits which have been determined from the crack initiation characteristics of the specific disk material, and will not address the problem of intrinsic crack-life defects. While damage tolerant concepts are utilized in some instances to establish life limits, the majority of components in current gas turbine engines have life limits set by an initiation criterion.

All fatigue data have inherent scatter. The data base used for design life analyses purposes must be applicable to all disks of a given material, and therefore includes test results from many heats and sources. Data are treated statistically as shown schematically in Fig. 2. The distribution of life, defined as the number of cycles necessary to produce a crack approximately 0.03 in. long, is obtained for a given set of loading conditions (stress/strain, time, temperature). As can be seen, the $\pm 2\sigma$ bounds, which contain 95% of the data, may span two orders of magnitude in fatigue initiation life.

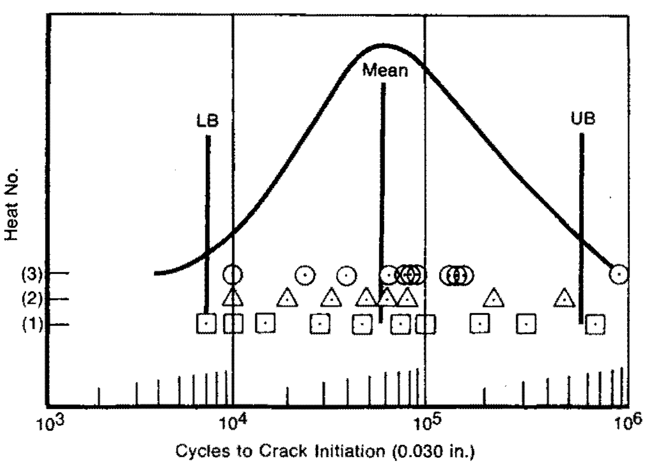

Fig. 2 Material data scatter results in conservative life prediction.

When considered with other uncertainties in any design system (e.g., stress analysis error, field mission definition, fabrication deviations, temperture profile uncertainty) the final disk life prediction is made for disk crack initiation life for an occurrence rate of 1 in 1000 disks. It is at this life that all LCF-limited disks are removed from service. This procedure has been very successful in preventing the occurrence of catastrophic failure of disks in the field. However, in retiring 1000 disks because one may fail, the remaining life of the 999 unfailed disks is not utilized. The amount of usable life remaining can be significant, as shown in Fig. 3, where over 80% of the disks have at least 10 lifetimes remaining.

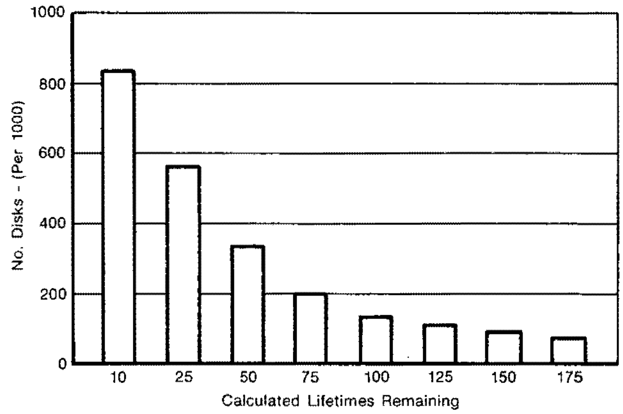

Fig. 3 The majority of disks have useful life after retirement.

The means of extracting the remaining useful life from each disk must be safe to avoid catastrophic failure. This done by determining the disk crack propagation life (N_p) (at every critical location) from a defect barely small enough to be missed during inspection. The Return-to-Service (RTS) interval is then calculated by conducting a Life Cycle Cost (LCC) analysis to determine the most economical safety factor (SF) to apply to N_p (RTS interval = N_p/SF). Cost vs SF is plotted for each individual disk and combined to determine the most economical interval to return a module for inspection. An example is shown in Fig. 4.

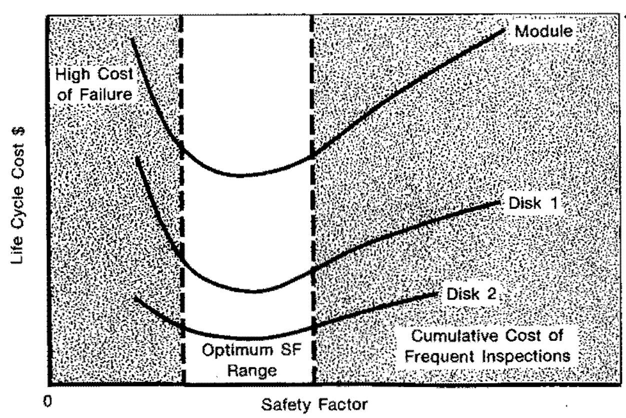

Fig. 4 Safety factor is determined from an economic balance between high cost of failure vs cumulative costs of frequent inspections.

The first required disk inspection is near the end of the analytically determined crack initiation life. Only one disk in 1000 inspected should have a crack and be retired. The other 999 will be returned to service for the calculated RTS interval. This inspection is repeated at the end of each RTS interval with the cracked disks being retired and all others returned to service. Figure 5 illustrates how the residual life is extracted from each disk after the crack initiation life has been used.

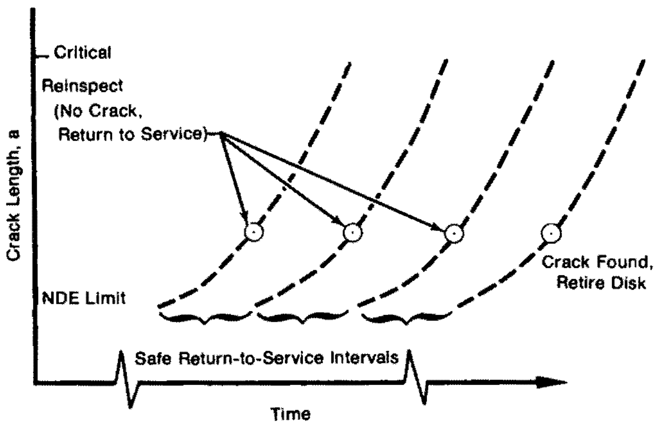

Fig. 5 Base Retirement for Cause concept.

TECHNOLOGY DEVELOPMENT REQUIRED

As Figs. 4 and 5 illustrate, Return-to-Service intervals are based on two broad technologies: Nondestructive Evaluation (NDE) and applied Fracture Mechanics, and evaluated based upon economic factors.

Fracture Mechanics must provide an assessment of the behavior of a cracked part should it pass NDE with a defect just below an inspection limit. To assure safe return to service of a part which may contain a small crack, an accurate crack propagation prediction is imperative. Recent strides in applied elevated temperature fracture mechanics[1-4] have provided the necessary mathematical description (models) of basic propagation, i.e., crack growth under conditions of varying loading frequency (υ), stress ratio (R), and temperature (T). Further work[5,6] has expanded this capability to include loading spectra synergism, i.e., crack growth subjected to (frequent) periodic major load excursions separated by a small number (10-50) of varying subcycles. It is important to note that a typical mission loading spectrum to which gas turbine engines are subjected bears little resemblance to that experienced by air frames, and therefore different predictive tools are required for each.[7]

Referring again to Fig. 5, it is seen that accurate propagation predictions constitute a necessary, but not sufficient, condition for the implementation of Retirement for Cause. The other requisite technology is high reliability nondestructive evaluation (NDE).

NDE must provide the means of screening disks with flaws that could cause component failure within an economically feasible RTS interval. Insufficient NDE reliability has been a major argument against implementation of an RFC maintenance program. NDE capability with acceptable flaw detection resolution has been available for some time,[8,9] but adequate reliability of flaw detection has been lacking.[10] Complementary inspections and improvements in NDE single inspection reliability (by automation), can provide the required reliability for many gas turbine engine components to economically utilize the RFC maintenance concept.

These two requisite technologies are integrated in the component life analysis.

The fracture mechanics approach to estimating component service life is based on the assumption that materials may contain intrinsic flaws, and that fatigue failure may occur as a result of progressive growth of one or more of those flaws into a critically sized crack. Thus, the prediction and monitoring of crack growth as a function of time (or cycles) becomes one of the basic requirements of the analysis system. To utilize such an approach in practice requires quantitative information on component stress, materials characteristics, and nondestructive evaluation (NDE) capabilities. Much of this information cannot be defined as a single value, but must be described by a probability distribution. Two examples are: the probability that a flaw of a given size will exist in virgin material, or the probability of finding a given flaw size with a standard inspection procedure. In order to obtain a deterministic fracture mechanics life prediction (given these distributions), the conventional approach has been to use worst case assumptions for all parameters. Employing all worst case assumptions for all parameters. Employing all worst case assumptions (deterministic) necessarily results in a conservative estimate for the service life of the component.

To circumvent this difficulty, the problem can be treated probabilistically. A closed-form solution, which takes into account all the required probabilities, is far too complex to be practicable. An alternative solution is to employ computer simulation techniques. A probabilistic life analysis[11,12] would use a distribution of flaw sizes. This type of analysis results in failure probability as a function of time, includes NDE reliability, and allows selection of an RTS interval to obtain an acceptable (low) failure probability with realistic NDE reliability.

Both deterministic and probabilistic methods could provide some of the NDE reliability through multiple inspections and/or through higher NDE limits due to shorter RTS intervals. Since many NDE errors are the result of human frailty, multiple inspection and automation can enhance detection reliability. The probabilistic system, however, has the ability to accommodate NDE reliabilty (probability of detection vs crack length) distributions and assess their effect upon RFC efficiency. Obviously, high reliability NDE is desired to optimize the economic benefits of Retirement for Cause.

The RFC Procedure - The Retirement-for-Cause (RFC) flow chart (Fig. 6) illustrates a simplified view of how this maintenance concept can be utilized. When an engine is returned for maintenance, an economic analysis is performed on the engine component/module identified as a participant of the RFC maintenance program. If the module has already been in service for several inspection intervals, the probability of finding cracked parts may be great enough to make reinspection economically undesirable and specific components of that module are returned without being inspected. This is determined by the economic analysis at decision point one and is one of three possible decisions. An unscheduled engine removal (UER) may bring a module out of service that is more economical to return to service for the remainder of its inspection interval than to inspect and recertify it for a new full interval (the second possible decision at point one). The remaining choice at point one is to tear down the module and inspect the parts. During inspection there again are three possibilities (decision point two). If no crack is found, the part is returned to service. If the disk is found to be unsafe, it is retired. The third choice is to investigate modification or repair of a flawed part. An economically repairable part may be repaired and returned to inspection (decision point three).

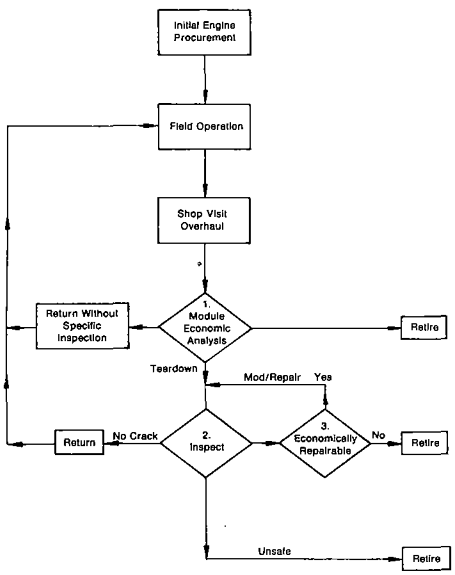

Fig. 6 Retirement for Cause procedure flow chart.

AN APPLICATION OF RETIREMENT FOR CAUSE

The application of a Retirement for Cause maintenance approach to a military gas turbine system has been studied and technology development progams are currently underway. The demonstration engine system is the USAF F100 engine. Under Defense Advanced Research Projects Agency (DARPA) and Air Force Wright Aeronautical Laboratories (AFWAL) sponsorship, a study entitled "Concept Definition: Retirement-for-Cause of F100 Rotor Components" Contract F33615-76-C-5172 (as modified in 1979) was performed. The results of this study are documented in AFWAL-TR-80-......, the final report for that program.

The objective of the program was to determine the feasibility of applying a Retirement-for-Cause (RFC) maintenance approach to the USAF F100 engine. The study was directed primarily toward rotating components of that engine, specifically the various disks and airseals/spaces that comprise the prime rotor structure. The technical effort consisted of five tasks:

- Define an RFC methodology and a means of assessing the ROI for its application
- Evaluate the disks of the F100 engine plus other appropriate engine rotor components for RFC applicability
- Assess nondestructive evaluation (NDE) requirements for implementation
- Establish a ranking of components for development priorities
- Establish development plans leading to implementation.

The methodology has been discussed in the preceding section of this paper. The component evaluations used a deterministic life analysis. Based upon this life analysis and life cycle cost analysis, 21 candidate components were selected, and development priorities established. Nondestructive evaluation requirements were determined for each of the components, and a development plan established, which when followed should enable implementation of RFC for the F100 engine in the 1985 time period.

The development plan is shown schematically in Fig. 7, and addresses the technology development requirements discussed previously. At the present time, many of these areas are the subject of Government contract procurement activities and cannot be discussed in detail. However, to illustrate some of the items which must be addressed, typical NDE requirements can be used as an example.

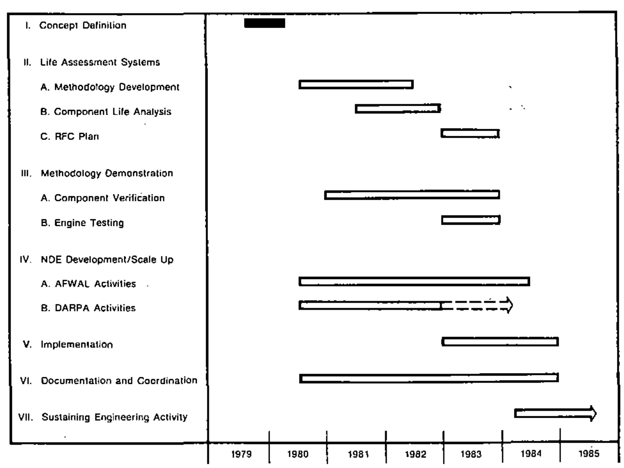

Fig. 7 Development plan engine component Retirement-for-Cause.

A composite sketch of typical gas turbine engine rotor components is shown in Fig. 8. As can be seen, the configuration of these components is complex and will require innovative techniques to enable reliable inspection. Examples of the types of defects which will require detection on these components are shown in Fig. 9. Techniques currently exist, such as eddy current, ultrasound and/or penetrants with the capability to detect these flaws. The major problem to be solved is detecting these flaws in a high volume maintenance environment, and integrating other techniques, such as proof testing, into a system with sufficient reliability to enable Retirement-for-Cause to be economically viable.

Benefits - The assessment of the benefits of a Retirement-for-Cause maintenance approach to a gas

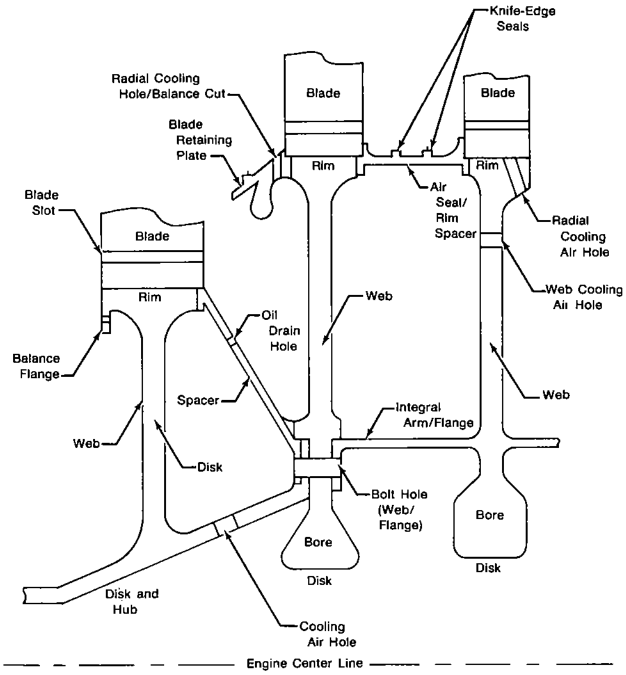

Fig. 8 Composite sketch of typical gas turbine engine rotor components (not all features are on all parts).

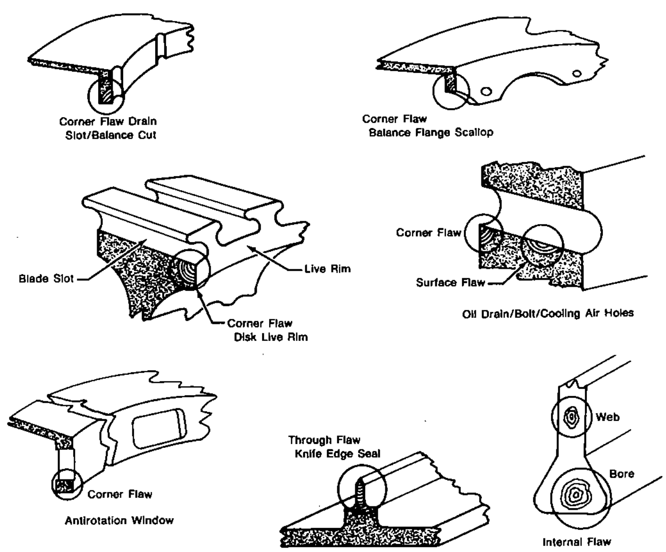

Fig. 9 Sketch of typical gas turbine engine rotor component flaw types.

turbine engine is contingent upon many assumptions. These assumptions include: fleet size, anticipated usage rates, usage life, inspection interval, labor costs, parts cost and many others.

To quantify the benefits of this maintenance concept for the USAF F100 engine, life cycle cost analyses were conducted. These analyses determined the change in life cycle costs of the F100 engine that could accrue based upon implementation of an RFC maintenance procedure in January 1985 as opposed to a continuation of current or baseline maintenance practices.

The life cycle cost benefits amount to an approximate $250 million savings over a 15-year period. In comparison to the investment required, the development and implementation of RFC are extremely attractive.

SUMMARY CONCLUSIONS

Realization and implementation of a Retirement-for-Cause Maintenance Methodology will result in system cost savings of two types: direct cost savings resulting from utilization of parts which would be retired and consequently require replacement by new parts; and indirect cost savings resulting from reduction in use of strategic materials, reduction in energy requirements to process new parts, and mitigation of future inflationary pressure on cost of new parts.

The methodology and procedures described herein are applicable to systems other than the F100 engine. A cursory review of other gas turbine engines indicates that the RFC maintenance concept is generic and has direct applicability to rotor components of those engines. In fact, the methodology has broad applicability to other types of engine components, and indeed, to systems other than aircraft gas turbine engines. The decision to apply RFC to other components or systems would be based upon economic factors, predicated upon the remaining anticipated service life of that system, and can be a viable maintenance concept for life limited components of all types.

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SUMMARY DISCUSSION

Bruce Thompson (Rockwell Science Center [now Ames Laboratory]): This community is particularly concerned with techniques that quantify in some detail certain of the flaw parameters. In your estimation of $200 million savings in life-cycle costs, what degree of quantification is assumed in the technique, and how much greater could that be if you had more quantification?

Jack Harris (Pratt/Whitney Aircraft): All right, I will now show you my Achilles heel. In order to conduct these life-cycle cost analyses, we used a 100 percent reliable NDE assumption. We know that's not true. Before you say that 250 million is wrong, we also used an extremely conservative estimate of life. They tend to balance each other. The answer is yes, we can get quantitative; we have defined life from assumed flaw shapes. Quantification of real flaw shapes would give us, I would say, a quantum leap in our accuracy of the predicted lives.

Mike Buckley, Chairman (DARPA): I was curious if Pratt and Whitney had ever looked at this concept in the sense of how it would impact the maintenance requirements, both scheduled and unscheduled and, therefore, the availability of the engine for performing its mission.

Jack Harris: We are in the process right now of an in-depth look at that from the unscheduled engine removal standpoint. We looked at it from the scheduled engine removal standpoint in the previous study, but one of the ground rules that we are operating on is that we are not going to let the forced readiness deteriorate from the levels at which it is currently operating. It is not going to get worse. The question that you're asking me is: Is it going to get better? I hope so, but I'm not sure. But it will not get worse. That's a given.

Mike Buckley, Chairman: You are also fixed by the current maintenance intervals?

Jack Harris: That's right.

Mike Buckley, Chairman: You didn't allow those to float, and I was wondering if in fact you had looked at that question. As the NDE gets better, clearly you can extend the interval safely.

Jack Harris: You can extend the interval safely. Again, we want to cause the least possible change in the current force structural maintenance effort. So we have tailored our Retirement-for-Cause concept to meet those current inspection intervals. There are techniques, for example, proof testing techniques, that would enable you to extend the intervals on certain parts. That's great, but it doesn't do any good on a three-stage fan if we can extend the interval on one part to 5 times but we can't extend it on the other part in the fan module. We have still got to bring the module in at an interval set by the lowest residual life part in the module. Yes, we hope we will be able to extend the intervals as we get further into the program. That remains to be seen. They won't get shorter than the present intervals. By definition, they won't get worse.

Joe Moyzis (AFWAL): When you say worse case, worse case, worse case, you assume a hundred percent reliability in NDE because what else can you do. Talking about realistic P.O.D., you mean a realistic P.O.D. in probabilistic fracture mechanics; is that right?

Jack Harris: Yes. What we hope to be able to do is integrate the entire NDE, life, and economic analysis into one tool that will enable people to make decisions. That is our goal.

John Rodgers (Acoustic Emission Technology Corporation): Taking an engine you essentially developed without Retirement-for-Cause in the conceptual design stages, and you now have an operational system, what do you think would be the economic benefit if you would take a design criteria and apply it to the F-100 today and redesign the engine to take full advantage of quantitative NDE and Retirement-for-Cause analysis? What do you think the resulting factoral economic benefit would be over what you projected in this conservative situation?

Jack Harris: To be honest with you, we can do that today. It is called damage tolerant design, and it is a concept that a lot of people now apply. Unfortunately, it is one of those situations where you can't have your cake and eat it, too. The damage tolerant design concept would enable you to, in effect, design in Retirement-for-Cause from day one. You <u>can</u> do it. There have been some innovative techniques come out our Air Force aero-propulsion lab-sponsored program that say the weight penalties are not going to be near what we thought they were going to be but there would still be weight penalties. Obviously, if the part's going to last - be able to sustain a known flaw for three overhaul increments, the part has to be bigger, it has to be heavier, the stresses have got to be lower so that our weight penalties - I wouldn't even try to make a guess at quantifying that benefit. I think we are premature there. I think within a few years we will have the damage-tolerant design techniques that will enable us to put a very attractive engine, from a weight-performance standpoint, in the field and still get the benefits of Retirement-for-Cause.

We were amazed at the results of this study. We did not design the F-100 engine to operate on a Retirement-for-Cause basis. It was designed to provide the maximum possible performance at the minimum possible weight. Consequently, we went to very high stresses. We have gotten the performance out of it. We have gotten minimum weight, but we have been astonished to find we can also use Retirement-for-Cause for a significant number of it's parts. Maybe that's serendipity. I don't known, but it sure looks good.

Mike Buckley, Chairman: Have you people worked on the viewgraphs to display to the Air Force some of the disk failures depending on how much maintenance and how many redundant inspections are performed as a function of money? Once you get to a real reliability case, you're going to have to accept a given probability of failure at a given cost, and, of course, we do today, but people don't like to admit it. They still believe it's a perfect system. Has ther been much thought on that yet?

Jack Harris: Yes. I think it would be premature for me to really discuss it, Mike. For the benefit of all of you who are not aware, we will be entering very shortly into a four-year development program to obtain the necessary fracture and life methodologies. We feel we have the firm foundation for that. We have to pull them together and integrate them. That program will start momentarily, I hope, and possibly next year we might be able to discuss that. Yes, we have looked at that. We have made an assessment of how many failures per thousand or per unit might occur and so on.

Mike Buckley, Chairman: That, of course, will be impacted by the quality of the inspection. Procedure to a very large degree and this is where, in many ways, a reliable system is a quantitative system when you get right down to it. There can be other things which destroy that, but -

Jack Harris: Yes, possibly one thing that I may have glossed over. And I certainly didn't do it intentionally. We are looking, as I said, at very uniquely located and oriented flaws in very complex configurations. It would be great if they were just machined, but they're not. They come out of the field; they come into an overhaul system. They have oil on them, they have coke on them in some cases; they're dirty; they may have stains on them; and you're going to have to handle something like 1,000 to 1,200 of those parts a month. It's a pretty large undertaking.

Mike Buckley, Chairman: Last question, Otto,

Otto Buck (Rockwell Science Center [now Ames Laboratory]): Given the detectability of five mils, given a fracture, certain fracture toughness, I guess that the design life is seven years now for the engine?

Jack Harris: The Air Force likes to say the life of the system, just like Arden Bement said, is 15 years.

Otto Buck: What is your estimate at the present time for an inspectable period? How often would you have to inspect? Roughly. Do you have any estimates on those times at the present time?

Jack Harris: Currently, you're dealing with cyclically life-limited parts. The time, in effect, becomes a factor of how many cycles a part accumulates. If you project under the current flight accumulation schedules for the F-15 and F-16, it indicates that you will accumulate a maximum of 12,600 cycles in a 15-year time frame. Beyond that, I would say I would have to do some back-of-the-envelope calculations.

Otto Buck: Two years?

Jack Harris: Figure it out. Divide 15 into 12 and figure how many cycles a year.

Mike Buckley, Chairman: The intervals are established by cycles and they are currently set.

Jack Harris: And equivalent to some service usage. Maybe three years, for example.

Unidentified Speaker: You said 39 tons of cobalt. How many engine disks is that?

Jack Harris: How many engine disks is that? It is anticipated that before the last F-100 engine is retired and melted down, there will be somewhat in the neighborhood of 7- or 8,000 of these engines in the free world, maybe a few of them in the unfree world. But if you look at that, and you just figured how many of these disks, 14- 15,000 nickel-based disks, you're talking about a high percentage volume of cobalt. I can't remember the exact percent, but it's greater than 10 percent by weight in each one of these disks. You work back, and that's how they come up with 39 tons.

The alloys we're looking at are titanium 6246 waspaloy, astroloy and IN-100. The latter three are all cobalt-bearing alloys.

Otto Buck: As far as I know, the materials people right now are trying to make an effort to take the cobalt out of the super alloys, which will help, too.

Jack Harris: There are alloy development programs under way to either go with non-cobalt containing super alloys and develop the processing to get them to equivalent strengths, or to reduce the amount of cobalt used per a given component by new forging techniques. Net shape forging, for example, and a lot of those.

Mike Buckley, Chairman: Thank you very much, Jack.